Fusion of ground penetrating radar and acoustics data

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ABSTRACT

An effort is underway to develop a fused sensor system for effectively detecting both metallic and non-metallic landmines. This advanced research effort will meld two orthogonal technologies, acoustic-to-seismic coupling and ground penetrating synthetic aperture radar, into a single system with a higher probability of detection and lower false alarm rate than either technology can achieve individually. Previous testing has demonstrated that these two technologies have individually high probabilities of detection and low false alarm rates but exploit disparate phenomena to locate mines. The fact that they both produce similar data makes a high confidence "mine/no mine" decision possible. Future plans include a stepped development process to build a close-in detector and leveraging that experience to develop a forward-looking system capable of meeting long-term Army requirements. This effort is sponsored by the U. S. Army Communications-Electronics Command Night Vision And Electronic Sensors Directorate.

Keywords: fusion, acoustics, ground penetrating radar, laser Doppler velocimetry, land mine detection.

1. INTRODUCTION

Recent struggles in foreign lands have highlighted the need for effective mine detection sensors. An effective sensor pinpoints the mine location with a very high probability of detection and a very low false alarm rate. The mines encountered today come in a plethora of sizes and materials and are buried at various depths, in various types of soil, and under various conditions. This confluence of variables is weighted against an ability to rely upon a single sensor. Most sensors have both strengths and limitations. Sensor fusion provides an opportunity to meld together two or more sensors to complement one another's strengths while compensating for weaknesses. The end result is a significantly higher probability of detection and lower false alarm rate, with obvious benefits to the warfighter. The trick is to identify sensors that are truly orthogonal, that exploit disparate phenomena to locate mines while producing similar data that can inform a single "mine/no mine" decision. The University of Mississippi (UM) and Planning Systems Incorporated (PSI) have independently developed two technologies that meet these criteria: acoustic-to-seismic coupling (A/S) and ground penetrating synthetic aperture radar (GPSAR).

Both technologies have proven to be highly successful in independently-scored blind testing sponsored by the U. S. Army yet they exploit completely different physical phenomena to pinpoint mines. The UM's A/S technology exploits the mine's resonance response to acoustic-to-seismic coupling of sound into the ground while PSI's GPSAR identifies differences in the dielectric properties between the ground and buried objects. However, the two systems produce data in common geospatial coordinates making fusion at a pixel level possible.

The two systems complement one another admirably. At shallow burial depths, the GPSAR signature of the mine is difficult to separate from the ground return, yet this is where the A/S signature is strongest. At depths of six inches or greater the A/S signature becomes larger in extent and weaker in strength, yet the GPSAR has little trouble identifying the mine. In extremely moist soil, the attenuation of the radar signal becomes large, but the A/S signal is minimally affected. The acoustic technique works in short grass but has problems with fallen leaves and may not work in high grass, yet these conditions pose little problem for GPSAR. A/S detection appears to work best against plastic mines due to their higher resonance, while GPSAR appears to work best against metal mines due to the large contrast in dielectric properties between soil and mine. The two

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sensors have comparable resolutions of a few centimeters, which allow fusion at the pixel level as well as other types of fusion.

The next step is to integrate both systems onto a single platform with a common data system. The first generation of this fused system will employ the relatively mature current technology to create a close-in detector. This close-in system will then be used as a springboard to produce a forward-looking system for use in standoff detection. The standoff system will use the same data system as the close-in system but will employ sensors capable of looking downrange. Initial tests of the forward-looking sensors indicate the promise of this capability.

2. THE A/S SYSTEM

The University of Mississippi's A/S detection system locates mines by insonifying the ground and measuring its vibrational velocity within a two-dimensional area. Loudspeakers broadcast pseudo-random noise in a frequency range from 80-400 Hz, a range based on the natural frequencies of buried landmines. The acoustic energy enters the porous ground and is coupled into seismic motion of the solid matrix of the soil. This energy causes the compliant top of the mine to resonate and the energy is returned to the surface where it causes increased vibrational velocity. The area of increased vibrational velocity is approximately the same size and shape of the mine. Because mines resonate while most natural objects buried in the soil do not, this technology is relatively insensitive to clutter. The ground velocity is measured using a laser Doppler vibrometer, a non-contact sensor.

The general current setup of the University of Mississippi A/S apparatus is shown in Figure 1. The laser beam moves from point to point on the ground and scans a grid. The grid spacing is set to one third or less of the diameter of the expected mine and is never greater than 10 cm. Thus the mine is spatially oversampled. The surface vibrations are measured at various frequencies over a selected band, which is within the frequency range of 20 to 400 Hz.

The signature of a mine is a cluster of grid points representing increased surface velocities that roughly form a circle. This detection of multiple adjacent points is very robust since recognition of the presence of a mine is not based on single point detection. Down to a burial depth of up to six inches to the top of an antitank mine, the signature is still quite clear. The strength of the signature is sensitive to the resonance characteristics of the mine and is strongest at the natural frequency of the mine. Typical optimum frequencies are 175 Hz for antitank mines and 300-400 Hz for antipersonnel mines. Additional details about the A/S detection system are given in Reference [2].

Currently, identification of a mine is based on an area of increased velocity that is the correct size and shape for a mine and that remains constant when viewed in multiple frequency bands. The U. S. Army Communications-Electronics Command Night Vision and Electronic Sensors Directorate is currently sponsoring a separate program to devise automatic target recognition algorithms to improve mine recognition resulting in a higher probability of detection.

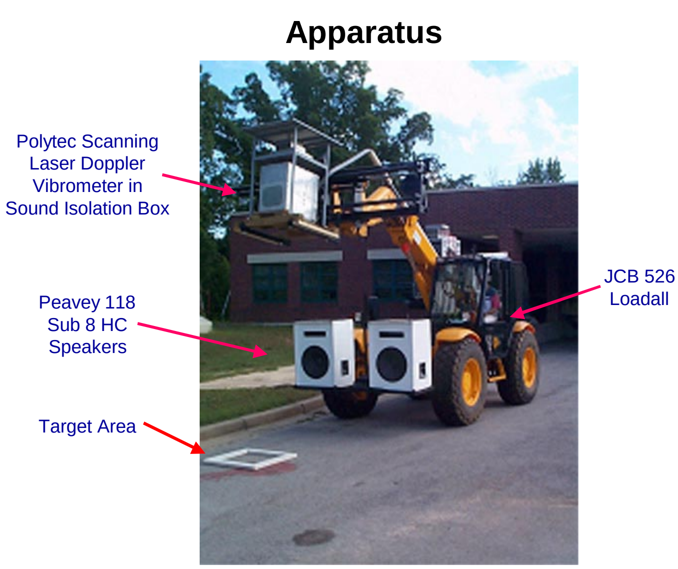

Figure 1. A/S detection system with a laser Doppler vibrometer.

3. THE GPSAR SYSTEM

The ground penetrating synthetic aperture radar (GPSAR) developed by PSI finds mines by producing a detailed spatial map of changes in the dielectric reflective properties of the ground. A photograph of the GPSAR system as configured in November 1999 is shown in Figure 2.

The radar electronics of the GPSAR system operates the antenna banks shown in Figure 2, each of which contains seven transmitter and seven receiver antennas. Each antenna bank has a dedicated radar module that operates over the frequency band 500 to 1800 MHz. A radio frequency (RF) switch bank is used in conjunction with the antenna bank to acquire data from equally-spaced locations for each of the two antenna banks. Along-track resolution is obtained via forward motion of the system with data acquisition at prescribed intervals initiated by a mounted optical encoder. The resulting two-dimensional data grids are processed using synthetic aperture, nearfield beamforming to produce volumetric images of buried objects.

The current sweep width of the GPSAR system is approximately one meter. The back and front antenna banks each record data over 13 equally spaced points. These two antenna banks are offset by 1.38 inches in the cross-track sense. Thus, the combined cross track spatial sampling of the system is 1.38 inches. Log spiral antennas are used. The transmitter and receiver antennas are wound in opposite directions in order to minimize direct coupling effects. Due to the directional nature of these antennas, the system is not plagued by hyperbolic-shaped image anomalies common to other ground penetrating radars. Under normal operating conditions data is recorded at 66 equally spaced frequencies over the 500-1800 MHz band. The depth resolution of the system is approximately 3 inches. The heights of the antenna arrays above the ground are electrically adjustable, thereby facilitating data collection at different antenna heights. In its present configuration, the GPSAR can move forward at a speed of about 1000 ft per hour, depending upon frequency sampling interval, total bandwidth and along-track sampling increment. By using additional radar modules and faster digital circuits, significant increases in operational speeds of advance for the system can be achieved.

Figure 2. GPSAR in action. Major system components visible in this photograph include the front and rear antenna banks and the onboard laptop computer. The radio frequency switches that switch a single-channel, stepped-frequency radar across each antenna pair are located directly above the antenna banks. The radar electronics are located between the front wheels of the radar cart and the battery is located between the rear wheels.

4. SIMILARITIES IN DATA FORMATS

The University of Mississippi's A/S sensor and the PSI GPSAR both record data in three dimensions, two of which are spatial (cross track/along track denoted by *xy*). The GPSAR records an *xy* spatial map of the ground's complex frequency response. This frequency domain data is converted to a time/depth representation using Fourier transforms or their analogs. Similarly, the A/S sensor records frequency-dependent velocity data that is resolved through use of a Fourier transform at each *xy* coordinate. Since both systems collect similar types of data across identical *xy* coordinates, sensor fusion at the pixel level is feasible.

Figure 3 shows sample images produced by both systems. The target in question is an M19 plastic mine buried at 5 inches depth on Calibration Lane 13. These images are presented on a color-coded intensity scale. The A/S image (3a) covers a one square meter area and is shown in a frequency band of 120-130 Hz. The mine is identified by a high velocity circular shape approximately 12 inches in diameter near the center of the image.

GPSAR images of this same mine are shown in Figure 3b. The top of this figure shows the *xy* display and the lower portion of Figure 3b shows the corresponding depth slice image. The GPSAR imaged a volume that was one-meter by one and one-half meter square and 12 inches in depth. Since volumetric images are difficult to display graphically, the maximum intensity is mapped onto the *xy* coordinates and the maximum intensity is mapped onto along-track/depth coordinates to produce the side view display.

The GPSAR *xy* display is most similar to the A/S image. Cropping the GPSAR image so that it corresponds to the same *xy* coordinates as the A/S image allows direct comparison of the two system's resolution. In producing these figures, there has been no attempt to exactly align the "hot" spots produced by the mine.

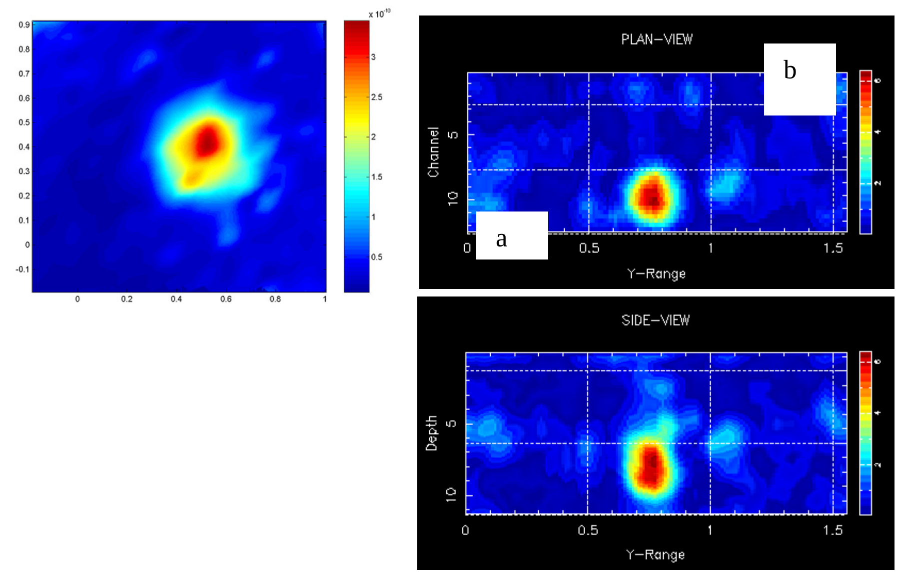

Figure 3. a. Image of an M19 plastic mine buried at 5 inches in Lane 13 produced with the A/S system. **b**. Images of the same M19 plastic mine buried at 5 inches on the Lane 13 produced with the GPSAR system.

5. SIMILARITIES IN PERFORMANCE MEASUREMENTS

After identifying mine technologies that use different physical phenomena to locate landmines and after ascertaining that similar data may be produced to permit fusion, the next step is to ensure they perform well. The metrics for effective mine detection are clear: a high probability of detection, a low false alarm rate, and a low circular error probable (CEP) in pinpointing the mine location. To demonstrate the capabilities of these two technologies, they were subjected to blind testing on sites located in Lanes 2, 3, 4 and 5.

In April of 1999 the A/S system was subjected to independently-scored blind testing in which data was collected over 19 mines, 31 blank spots and 9 additional spots known to produce false alarms in multiple other ground penetrating radar systems [3]. In November of 1999, the GPSAR system was also subjected to blind testing in which data was collected over 17 mines and 31 blank spots [4]. For each spot, the area imaged was one square meter. Each team examined the real-time images of the collected data and decided whether or not mines were present on the spot.

In these blind tests, the A/S team scored a P_d of 95 percent with one false alarm for a P_{fa} of $0.03/m^2$ including no false alarms over the 9 ground penetrating radar clutter spots. Positional accuracy was within 5 cm. The GPSAR team scored a P_d of 76 percent with one false alarm for a P_{fa} of $0.03/m^2$.

Figure 4 shows images of two mines from the April/November 1999 blind testing in which both the A/S and GPSAR systems correctly identified the presence of a mine. The mines shown in the figure are an EM12 at 1-inch depth and a VS22 at 2-inch depth. These are both plastic mines at shallow depths and both systems imaged them clearly and accurately. The A/S and

GPSAR images are presented full range with no attempt to eliminate clutter. Conversely, Figure 5 shows images from two sites where the A/S and GPSAR systems both correctly declared that no mine was present.

Images from two sites in the blind test in which the GPSAR incorrectly declared no mine was present are shown in Figure 6. In each case the target missed by the GPSAR was a plastic mine. The A/S system correctly identified the presence of mines at these two sites.

Figure 7 shows images from two of the nine places that were known to produce false alarms in multiple other ground penetrating radar systems. The GPSAR was not subjected to blind testing at these sites; however data was recorded at these nine sites with an earlier version of the GPSAR system in April of 1999. An examination of this data by PSI indicates that these nine sites would have produced four GPSAR false alarms. Data from two of these four sites is compared to the corresponding A/S data in Figure 7. As previously mentioned, the A/S system produced no false alarms at these nine sites.

Figure 8 shows images produced by the A/S and GPSAR systems of two deeply buried mines located in an off-road lane. The left side of the figure shows the return from an M21 mine buried at 6 inches. The right side of the figure shows the return from an M21 mine buried at 8 inches. The A/S system has difficulty in detecting the deeply buried mines. The mine at 6 inches depth is not visible at all while the mine at 8 inches depth is only faintly visible. To demonstrate the complementary strength of the GPSAR system, it readily detects the two deeply buried metal mines.

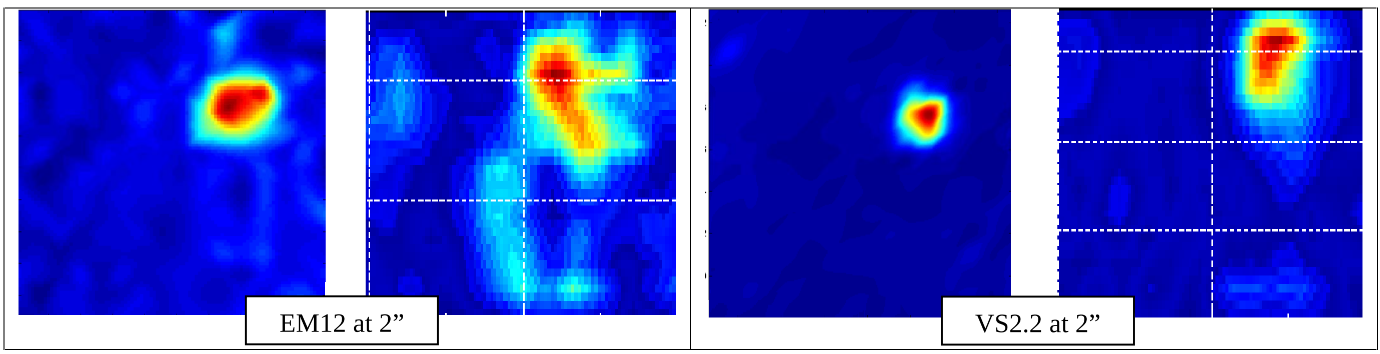

Figure 4. Images of mines in the April/November blind testing in which both the A/S and GPSAR systems correctly identified the presence of a mine. Site 219, on left, EM12 at 2-inch depth. Site 229, on right, VS22 at 2-inch depth. For each image pair, the A/S image is shown on the left and the GPSAR image is shown on the right. In each case the imaged area is one meter by one-meter square.

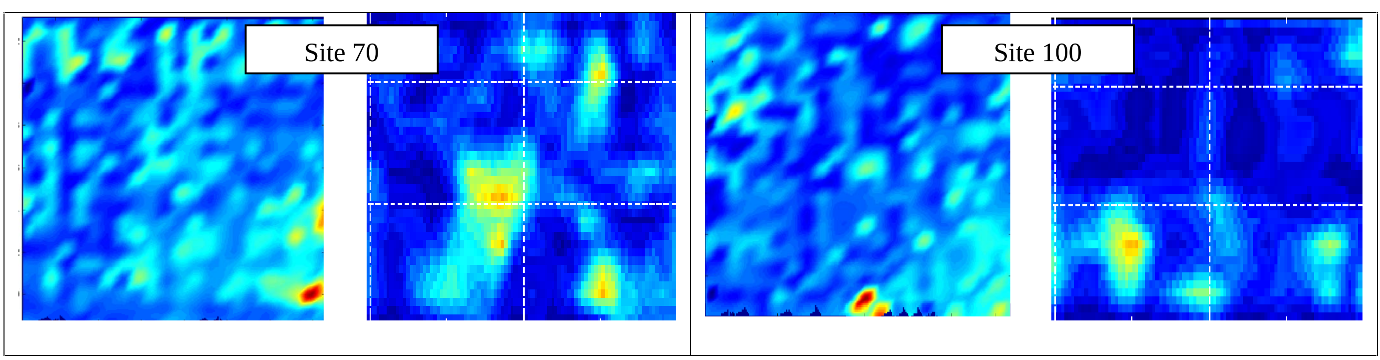

Figure 5. Images from sites in the April/November blind testing in which both the A/S and GPSAR systems correctly declared no mine was present. Site 70, on left. Site 100, on right. For each image pair, the A/S image is shown on the left and the GPSAR image is shown on the right. In each case the imaged area is one meter by one meter.

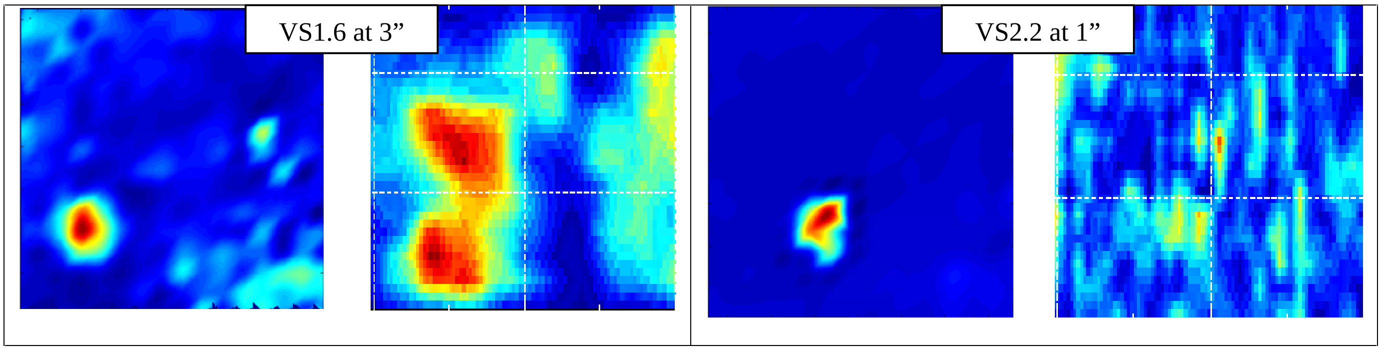

Figure 6. Images from sites in the April/November blind test where the GPSAR incorrectly declared no mine present. Site 90, left, VS1.6 at 3". Site 125, right, VS2.2 at 1". The A/S system correctly identified the presence of mines. For each image pair, the acoustic seismic image is shown on the left and the GPSAR image is shown on the right. In each case the imaged area is one meter by one meter.

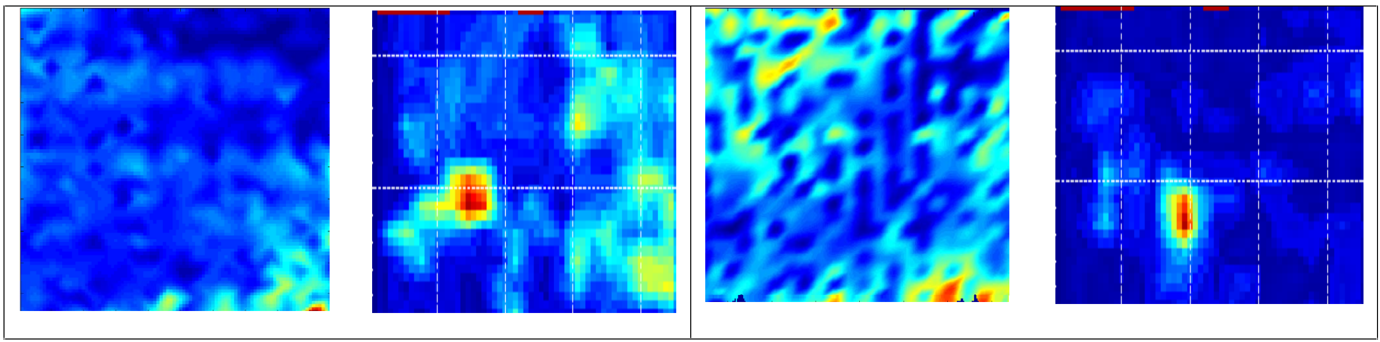

Figure 7. Images from two known high GPSAR false alarm spots in the April blind test where the A/S system correctly declared no mine was present. The A/S image is shown on the left and the GPSAR image is shown on the right. In each case the imaged area is one meter by one meter.

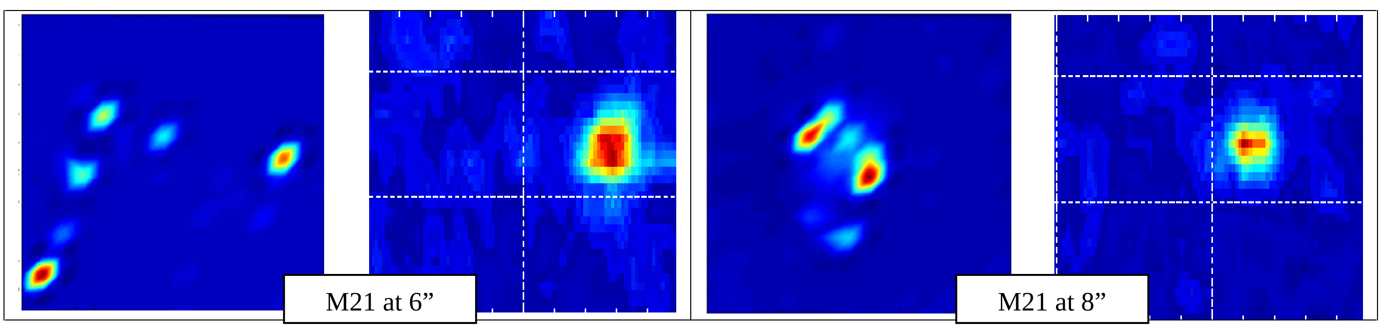

Figure 8. Images of two deeply buried mines in an off-road lane. The left side of the figure shows the return from an M21 mine buried at 6 inches. The right side of the figure shows the return from an M21 mine buried at 8 inches. The A/S image is shown on the left and the GPSAR image is shown on the right. The imaged area is one meter by one meter.

6. FUTURE PLANS

Future plans call for a stepped approach leading to a forward-looking fused system for use in a standoff mode with future Army combat systems. The next step in the development of a fused system is to mature the two technologies and develop an integrated A/S-GPSAR, close-in, mine detection system. The system will be integrated on a small, electrically-driven vehicle. The A/S-GPSAR system will provide real time mine detection, data processing including image generation, automatic target recognition, and data archiving. The system will also provide geodetic mine location using precision Real Time Kinematic (RTK) GPS technology. Figure 9 illustrates a configuration for the close-in A/S-GPSAR system and vehicle.

Figure 9. A/S-GPSAR Concept Drawing

The primary hurdle to overcome for close-in detection is increasing the scanning speed of the A/S system. Several initiatives are in progress to accomplish this. The first is the use of a continuously-scanning LDV. Initial testing using a moving beam controlled by mirrors indicates scanning speeds up to 1.6 m/s or greater are feasible (as shown in Figure 10), resulting in an increase in scanning speed from approximately 20 minutes per square meter to about 10 seconds per square meter. Building on that success, an array of 16 LDVs is under construction to simultaneously collect data in parallel. MetroLaser, Inc, is currently developing a single LDV with 16 beams that will replace the 16 separate LDVs to reduce system volume and weight and to simplify data acquisition and processing. Other initiatives to increase speed are research into alternative sensors that may collect data over large areas in a single measurement and implementation of automatic target recognition algorithms to locate mines without human intervention.

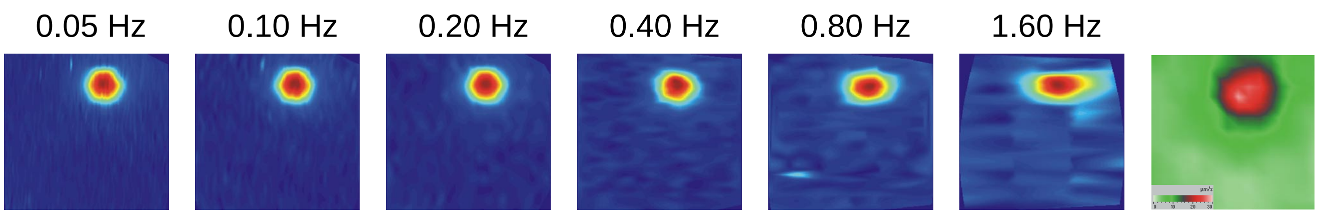

Figure 10. Images of a VS2.2 landmine buried at 1-inch depth. The area of each image is 1m by 1m. Scanning speed (in terms of hertz) is the time to scan a line 1m long. The image on the right was made using the traditional raster scanning method.

The second step is development of a vehicle-mounted forward-looking land mine detection system. In general, development and engineering of the downward- looking system leads that of forward-looking systems. This lead-lag effect is caused by the challenges imposed in forward-looking systems. Two factors make forward-looking systems more challenging. The first factor is the considerably longer sensor signal path lengths and resulting signal loss. The second is the shallow angle of incidence that causes most of the signal to be lost rather than returned for detection. For example, the A/S and GPSAR sensors and detection electronics must be optimized to counter the signal strength losses due to the longer signal paths and the effects of the shallow reflection or grazing angles.

The A/S system underwent forward-looking blind testing in May 2000 in which it scored a probability of detection of 68 percent with a false alarm rate of $0.01/m^2$. Several factors led to this score including the effects of incidence angle, laser instability, image distortion, and sound pressure level limitation. Initiatives are underway to improve performance in each of these areas, many of which are related. The angle of incidence causes the measured velocity of the ground to be decreased by the sine of the angle of incidence and the light from the LDV to become scattered with less reflection back into the sensor. The former effect may be overcome through increased sound pressure levels to cause greater excitation of the ground and more sensitive sensors. The latter effect may be resolved through the use of more powerful lasers. Since the LDV is an interferometer, sensor platform vibration causes significant system noise that must be overcome through passive or active vibration control.

The forward-looking GPSAR is in the early stages of development. Preliminary design efforts indicate that the antennas will form a Mills Cross Array. Performance will rely on near-field beamforming, which is closely related to the geophysical concept of migration. It serves as a computational basis for combining multiple “looks” at a mine and has been used successfully to image a calibration sphere buried one inch deep 7.2m in front of the antennas.

Underlying both of these detection systems is data system integration to provide proven, fast, and advanced digital signal processing to provide a single “mine/no mine” decision, improve signal to noise ratios, enhance detection capabilities, and reduce the false alarm rate. Advanced signal and data processing will employ real time Automatic Target Recognition (ATR) technology to improve detection and increase operability and speed by removing the human decision maker from the loop.

7. CONCLUSIONS

The A/S technology developed by UM and the GPSAR developed by PSI appear to meet the criteria for successful fusion of mine detection sensors. They exploit disparate phenomena, complement each other's strengths and weaknesses, and produce similar data in a similar format. Both systems have proven performance, high probabilities of detection with almost identically low false alarm rates, demonstrated through independently-scored blind testing. The success in meeting these criteria indicates that fusion of these two technologies can produce an effective mine detection system. Based on this promise, the University of Mississippi and PSI plan to fuse these two technologies for use in close-in and standoff mine detection.

VII. ACKOWLEDGEMENTS

The U. S. Army Communications-Electronics Command, Night Vision and Electronic Sensors Directorate supported this work.

VIII. REFERENCES

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